HIGH-SPEED DATA ACQUISITION FOR THE PRINCETON UNIVERSITY DYNAMIC MODEL TRACK

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ABSTRACT:

Real time analysis of data can reduce the time involved in exploring dynamic systems. The failure of the data acquistion system at the Princeton Dynamic Model Track prompted its replacement with a real time data aquistion system. Data can be obtained from an experiment and analyzed during and immediately following a data run. The new system employs high speed analog to digital conversion and a small computer to collect data. Sampling rates of 1000 hertz over 44 channels (44,000 words/sec) are obtainable. The data can be accessed as it enters the computer's environment where it may be displayed or stored for later processing. The system was tested on a helicopter rotor steep descent experiment. The data collected compares with previous data from a similar experiment.

INTRODUCTION:

The Princeton Dynamic Model Track was designed to study the performance, dynamics and control of helicopters and other VSTOL aircraft at low speeds, by means of testing dynamically similar models. The facility consists of a 750 foot long track with a cross section measuring 30 feet on each side. On one side, a set of rails runs the full length of the building . A carriage rides 15 feet off the floor along the top rail, while the lower rails supply power for the carriage's drive system and on board apparatus. The carriage has a hydraulic drive with servo control, which gives very steady velocity profiles, even at very low speeds. The capability for velocity and acceleration control is available from the on board analog computer. Semi-free flight experiments are possible when utilizing this capability. Models are mounted to one of the various booms which in turn are mounted to the carriage. Boom selection is governed by the type of experiment to be run. The Princeton Dynamic Model Track is more advantageous than a wind tunnel at low speeds, because the problems of wall interference and unsteady air flow do not exist.

The most recent methods for obtaining data used a direct analog recording system. In order to analyze the data, the recorder had to be removed from the carriage and then connected to an off-site minicomputer for processing. The original method of data acquistion involved direct recording by a 7-track recorder. Data was collected

using a tube-based telemetry system and a ground receiving station equipped with oscilloscopes and oscillographs was used for checking data validity after the completion of an experiment. Data processing would then be done as before; the tape had to be taken off-site and read and processed by Princeton's main IBM computer system. The digitized data would then be stored on tape for later use. This data acquistion system's eventual failure was inevitable due to its age. Faced with the decision to repair that existing system or replace it, the latter was the more attractive solution.

Data collection can be one of the most time consuming aspects in the analysis of any system. Efficiently determining the data's validity and experimental value helps to reduce the turn-over time between data runs. The new system allows users to examine data during and immediately after any particular run. With this capability, areas of interest can be quickly examined, thus facilitating the experimental process. A real time analog to digital data acquisition system has these capabilities. With data transmitted from a model to a ground station in digital form, the data can be fed directly into a computer and analyzed immediately. The Princeton Dynamic Model Track now has this capability.

THE AYDIN VECTOR BASED DIGITAL DATA SYSTEM:

System Overview:

The AYDIN VECTOR PDS-700 commutator samples 44 signals at a rate of 1000 Hertz. This data is then formatted into a serial stream output and broadcasted as a bi-phase logic pulse-code modulated (PCM) signal from an AYDIN VECTOR T605L transmitter at a frequency of 1431 megahertz. This PCM signal is then recieved at the control room by the AYDIN VECTOR RCC-201 receiver, where it is converted back to serial stream of data by the AYDIN VECTOR PAD-400 decommutator. Both the PDS-700 and the PAD-400 are fully documented.[1,2]

In theory, the sampling rate for a given experiment should be twice the highest frequency to be analyzed. In practice, higher sampling rates should be used to improve the results of spectral analysis. If we wish to study the blade dynamics of a rotor operating at 600 rpm, a sampling rate of 1000 hertz is ideal for seeing higher harmonics. However, when dealing with body motion or first

harmonic motions of the rotor, such a high sampling rate is unneccessary. It is also unlikely that 44 channels of data will need to be sampled for one experiment. To minimize the amount of incoming data, a buffering system was designed and built. The addition of this buffer eliminates unwanted data and aids in data processing.

An IBM PC/AT equipped with an HSD-16 digital I/O card recieves the data from the custom buffer. High-speed data communication with the AT is possible through direct memory access or dma. The HSD-16 card provides an interface between the incoming data and the computers memory. The capabilities and uses of the board are fully documented[3]. Dma allows data to be transferred at a considerable fraction of the machine's clock speed. When utilizing dma in the AT, transfer rates of 120,000 16-bit words/sec are obtainable. The AT is the last component of the data system, figure 1 below illustrates the general outlay of the entire system.

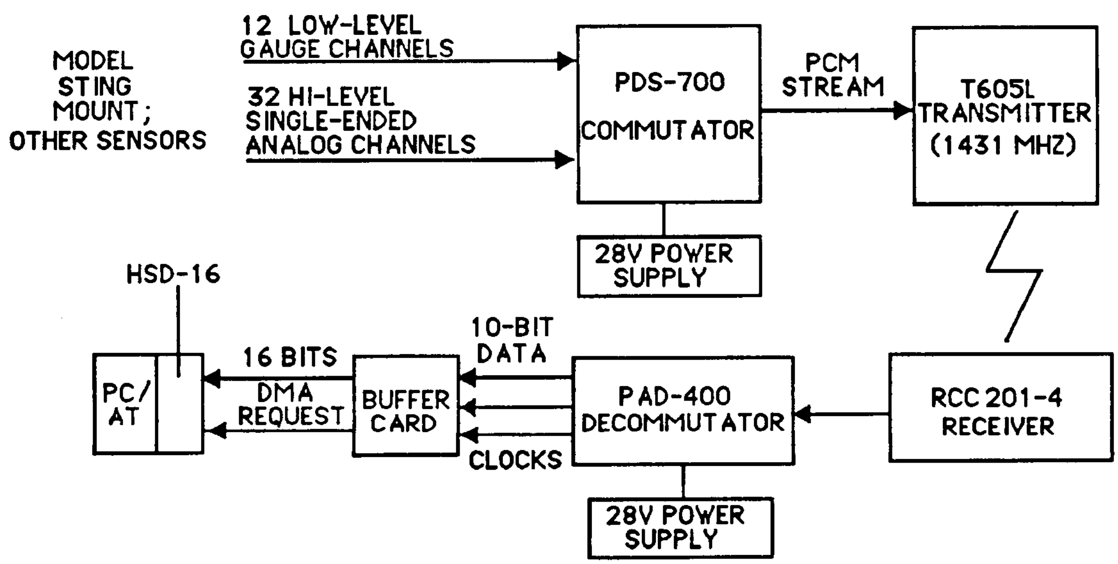


FIGURE 1

Data Collection and Transmission:

The PDS -700 has 32 hi-level single-ended analog inputs and 12 low-level strain gage inputs. Each gauge amplifier has programable excitation and gain so that no additional hardware is necessary. Each channel is equipped with a low pass 6-pole Butterworth filter, programmable from 5 Hz to 5 kHz. The channels are sampled at

1000 hertz and convertered into 10 bits of data, corresponding to a bit weight of 10 milivolts per bit with a range of +5 to -5 volts. This data forms a serial stream of 44 10-bit words. Two additional synchronization words are added to the serial stream. The PAD-400 utilizes the synchronization words to convert the serial stream back into a series of words and frames, with the 44 channels and synchronization words comprising one frame (see figure 2).

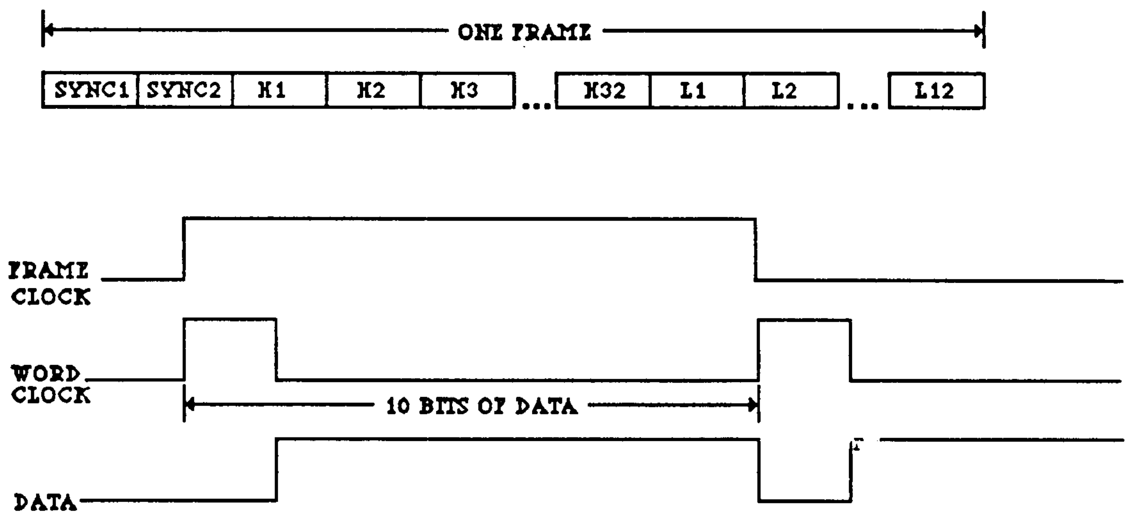


FIGURE 2

The buffer utilizes both the word and frame clocks to perform various functions. A frame clock divide is available to reduce the sampling rate by skipping a chosen number of frames between frames read. Dip switches that give the user the capability of turning off channels not being used in the experiment are also present. Each channel is also expanded to a 16 bit word, the six most significant bits containing the channel number of each data point. The dip switches are numbered from 1-48, 1 being the left-most switch. This numbering sequence corresponds to numbering sequence of the hi-level and low-level signals less one, ie. switch 5 turns on/off input 6. The combination of the channels selected and the frame clock divide are then used to create a dma request trigger. This trigger is the request to the HSD-16 card for a dma transfer. The red and green LED's are used to indicate if the PAD-400 is locked. The upper pair of LED's relays the status of the major lock and the lower pair is for the minor lock, a green LED signifies a locked condition. The three

test points from top to bottom are the frame clock divide, word clock, and dma trigger respectively. The toggle switch is used to turn on and off the dma trigger. A functional block diagram is given in figure 3.

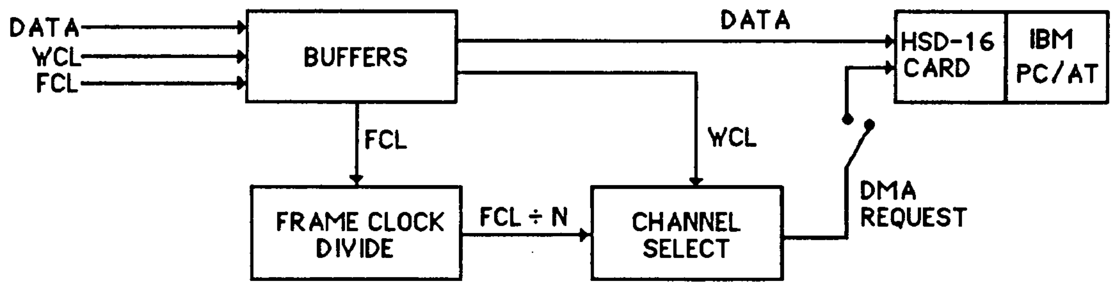


FIGURE 3

INTERFACING WITH THE IBM PC/AT:

About DMA:

Memory on this PC/AT is located by a 20 bit address. This address is determined by a segment and an offset. The segment makes up the 16 most significant bits of the address; the 4 most significant bits of the segment determine the page of memory. The major drawback of dma is that only one page of memory can be addressed at a time, thus transfers are limited to one page (one page = 65,5335 bytes). If the dma start address does not fall on a page boundary, then the largest transfer is determined by the number of bytes from the start address to the address of the next page. A larger transfer request will result in a 'page wraparound' in which data will continue filling memory at the beginning of the current page, instead of automatically going on to the next page of memory.

The HSD-16 card and Software Considerations:

The HSD-16 I/O card has been interfaced with the IBM AT through software in both high level and low level langauges. Some communication routines which interface with this board were written by ICS, the manufacturer of the board. This code was conveniently written in assembly so that it could be easily modified to interface with any higher level langauge. The card has several basic functions: card initialization, block I/O, transfer status, timer

control, word I/O, extra bit transfer, and interrupt enable and disable. In choosing a language to interface with the assembly routine, various factors had to be weighed. When dealing with data acquisition, it is practical if the user is able to explore incoming data. Thus manipulating the data without great difficulty is an important consideration. This aspect makes an interpreted langauge attractive because new code which handles the data can be quickly written and easily changed without compiling delays. One drawback of an interpreted langauge is that if iterative data computation, such as a Fast Fourier Transfer (FFT), is required, then the interpreted langauge becomes a slow and cumbersome tool. APL is an interpreted langauge which allows for easy manipulation of data, and, through use of interface software to compiled langauges such as C or assembly, iterative manipulations can be callable from the APL enviroment. With these considerations, APL was chosen to be the higher level langauge which would interface with the data acquistion card through the provided assembly code.

APL and Data Collection:

A front end was added to the HSD-16's assembly program which allows APL to pass and recieve variables necessary in running each of the functions. In the APL workspace DMA2APL, the menu driven function DMA provides an easy user interface with this program. Once DMA is entered, the user is then presented with 8 options corresponding to the 8 modes of the code. When a mode is selected the appropriate input data is requested by the program. After the data has been entered, APL calls the assembly routine and returns with appropriate error codes. A complete error code listing can be found in the HSD-16 hardware manual. By assigning a variable to the output of DMA, data can be fed directly into the assigned variable. This method is fine for small blocks of data, arrays with less than 10,000 elements; however with high data rates and multiple channels, data blocks become very large very fast. Larger data requests are obtainable by exiting APL and issuing DMA2FILE.

DMA2FILE is a program which was written to obtain large blocks of data. In order to collect larger amounts of data, the program performs a buffer swapping routine. While dma is filling one buffer, the other buffer is being written to a file. Dma status is then checked and the buffers are swapped once dma has filled the active buffer. This swapping continues until the determined amount of data has been written. A temporary file is created on the virtual disk to

expediate the writing of the data during the swapping routine. Once this file is filled, the user is asked to name the file in which the data will be kept. Data is then copied from the temporary file to the user defined file, located in the current directory. The temporary file is then removed from the virtual disk and the program exits. DMA2FILE is capable of obtaining 128k of data at one time, a limit determined by the size of the installed virtual disk. It is possible to increase this size, yet it is important to realize that the bigger the virtual disk becomes, the less memory is available for DOS and any other applications to be run, such as APL itself. The program requests the user for three inputs: the number of channels selected, the sampling rate, and the length of the time data collection will take place. It is imperative that the program receives the same number of channels selected as are selected via switches on the buffer box. This input is most imporant because of the time required to write the data to the file. The program uses the channel select input to determine the end of a frame, after which it writes data and swaps buffers. If the channel number does not correspond to what is actually sent, the swapping and file write will occur within a frame, between two channels, and the remaining data in that frame will be lost. A data loss will occur in every frame, and with the incoming data and the writing procedure out of phase, a different set of data will be lost in each frame, resulting in a non-contiguous data file. For the same reasons, it is also important that the dma trigger on/off switch be used to ensure that data is collected from the beginning of a frame. Messages are displayed which tell the user when the switch should be on or off. The time required in writing to a file is slightly less than one frame length, and thus DMA2FILE can only handle sampling rates of 500 hertz, every other frame skipped, or less. At 1000 hertz, the only higher available sampling rate, data can not be written to the virtual disk fast enough. If it is neccessary to use this sampling rate, the function DMA2PAGE must be used. It limits the amount of data to be taken to 64k, however, and is not user definable. The reason for this limit is due to the DMA page wraparound problem. Both DMA2FILE and DMA2PAGE have DOS error handling capabilities. If errors do occur, appropriate messages will be displayed with error codes in hex. See the *DOS Technical Reference* [4] for error code descriptions.

Data Retrieval, Processing and Display:

Once a file has been filled with data it is then possible to examine and manipulate this data in the APL environment. In the workspace

DMA2APL there is the function GETCHN, an assembly routine called from APL which performs DOS file handling routines to access a data file. When this function is entered, the first input requested is the file which contains the desired data. The drive containing that file must be specified, and if the file is not in the current directory, the file's path must also be included. The user is next asked which channel he wishes to obtain and how many data points he desires. GETCHN reads the file one word at a time, checking the six most signifigant bits for the chosen channel. Once the requested number of points has been found GETCHN returns with the requested data. If the number of data points requested exceeds the number of data points in the file for the particular channel, GETCHN returns a ¯1 for all surplus data points. If GETCHN returns all ¯1's, then the requested channel was not found in the specified file. If one assigns a variable to the output of GETCHN, then the assigned variable will be filled with the requested data. GETCHN will display messages relaying its status and will return any error codes if errors should arise. A complete guide to these error codes is located in chapter 6 of the *DOS Technical Reference*.[5]

A semi-real time digital oscilloscope is also available in the APL workspace DMA2APL. This function SCOPE, utilizes the graphics monitor to display the incoming data. Upon running SCOPE, the user will be asked for a variety of inputs; number of channels being sampled, sampling rate, time scale, channels to be viewed, scaling factors, and offsets. The program searches a data buffer for the chosen channels in a similar fashion to GETCHN and the retrieved data is displayed graphically. The data is then converted into volts; a value of 12 corresponds to -5 volts and a value of 1012 corresponds to +5 volts. This scaling scheme is what the PDS-700 uses in its analog to digital coversion. Scaling factors and offsets allow the user to scale and move data on the screen. The user may change any of the input parameters by simply hitting any key to return to the input field. After the RETURN key is hit the data will be displayed with those new parameters. The ESC key is used to exit the program. The SCOPE is a good tool for checking data validity before issuing any large block transfer of data.

As previously mentioned, APL is a good langauge for manipulating data quickly, but performing DMA with APL resident can be very dangerous. APL has access to all available memory. If DMA is taking place where APL is expecting free memory, random and probably hazardous events are bound to happen, with the event

of a total system crash not unlikely. DMA is given a segment and offset in memory from which a 20 bit address is determined. Data is then written directly to this memory location. When an APL variable is filled using DMA, that variable's segment and offset are determined and data is fed directly to that location. If APL should chose to move the location of that variable in memory during DMA, the events aforementioned will happen. APL will only move variables around if others are created or destroyed; it is therefore wise to avoid any workspace modification while dma is in progress. Users should also be wary of the auto-initializaton option when issuing "dma to an APL variable". This option is not to be used when filling a variable and should always be set to 0. Auto-initialization tells the DMA controller to keep filling memory with the requested number of bytes and always start filling at the same location. This loop of continuous fill will proceed until another DMA is requested. APL is bound to reconfigure memory given time, and if auto-initialization is in effect, DMA will write to some place it should not. The function SCOPE does utilize auto-initialization, but the memory in which DMA is taking place is occupied by the virtual disk and is out of reach of APL. This memory is not out of the control of DOS, however, and if any files reside on the virtual disk when SCOPE is running, other dangerous events may happen. Those files may be seriously damaged or, worse, a parity error may occur. To recover from a parity error, the machine will need to be powered down in order to reboot it. Users should make sure the virtual disk is empty by issuing a ")cmd dir d." from APL before running SCOPE.

In addition to the DMA2APL workspace, there are two other workspaces available for off-line processing and graphing. These workspaces can be accessed directly from the DMA2APL workspace. PLOTDATA contains a set of graphics routines which can be used to plot the data a number of ways. The other workspace is SPECRTRAL and has a number of spectral analysis tools associated with it. Included in both workspaces is a copy of GETCHN to aid the user in obtaining data from files. If the active workspace is DMA2APL, PLOTDATA, or SPECTRAL one of the remaining two workspaces may be loaded by simply entering the name of the desired workspace. The user can then return to the previous workspace by hitting the F1 key.

In the workspace PLOTDATA the user may display data on the enhanced graphics monitor or get a hard copy of the graph on the plotter. The function AUTOPLOT will scale data to fit on the screen

and draw axes corresponding to the scaled data. A title and axes labels are also available. The function PLOT is similar to AUTOPLOT except that the parameters used in displaying the data on the screen are not automatically determined. When using PLOT, the function USERSCALE must first be used to set up the graphing parameters. USERSCALE sets up an input field in which the previous graphing parameters are displayed. Any of these parameters may be changed accordingly. The title, axes labels, display colors, and other parameters can be changed by entering USERSCALE. The function PLT is useful for displaying more than one graph for a given set of scaling factors and axes. PLT will display the data without redrawing the axes, title, and labels. The color the data is drawn in may be changed by entering USERSCALE. The variable HPON determines whether or not plotting data will be sent to the HP-7475A plotter. When HPON is 1, functions will plot on both the monitor and the plotter, a value of 0 will result in graphing on the monitor only. The function CLEAR will clear the graphics monitor for a new graph. An on-line description of these functions is contained in the variable DESCRIBE, which is displayed upon entering the workspace.

SPECTRAL contains a variety of spectral analysis tools. The function FFT utilizes an assembly routine for speed. Data must be dimensioned as a $2x2^M$ array; the first row of data being its real component and the second row being its imaginary component. The function SPECTRA computes the I/O cross power spectra of a $2x2^M$ I/O sequence. The first row is composed of the input power spectrum with the output power spectrum residing in the second row. The output of SPECTRA can be used in either XFERFN, COHERENCE, or S2NRATIO. XFERFN determines the transfer function of the I/O sequence as a function of frequency while COHERENCE will compute the coherence between the output and input sequence from the cross power spectra data. S2NRATIO computes the signal to noise ratio of the output as a function of frequency. The magnitude and phase of the transfer fuction can be determined from the functions MAGNITUDE and PHASE respectively. The input to these functions is the output of XFERFN. The function RANDSAMP is also available in this workspace for generating a sequence of random numbers. As in PLOTDATA, the variable DESCRIBE provides an on-line description of these functions.

TRACK AND CARRIAGE OPERATION:

System Overview:

An on-site 400 cycle generator supplies power to the hydraulic drive and various carriage devices. The carriage is propelled by a hydraulic servo pump drive system which provides very smooth velocity profiles. The drive system is controlled by yoke displacement.

Preliminary Inspection:

An inspection of the entire length of the track should take place before any power is supplied to the rails; nothing may lean against the rails or obstruct the path of the carriage. Any objects which have the potential of falling on the rails or into the path of the carriage must also be secured. The copper power buses located in the rails should also be checked for any anomalies. These buses are prone to thermal expansion and contraction and may buckle as a result. Severe deformations of the buses must be corrected. Splices in the buses should also be inspected for any breaks.

The air compressor should also be inspected prior to any operations. It is needed to inflate the carriage tires and to check the hydraulics on the carriage. The tank should be drained of any water which may have accumulated in it. The red valve handle on the lower right side of the tank should be opened to accomplish this task and closed again when there is no further flow of water. Tank pressure should be approximately 90 psi. The oil level should be checked on a weekly basis if the compressor is in frequent use. Make sure that the compressor is off before checking the oil level in the compressor motor. Add oil as necessary; the plug is on the lower right side of the motor. Once the tank is up to pressure the blue valve should be opened. This valve is the feed to all of air hoses in the building. The compressor should be shut down on weekends and during other extended periods when it is not needed, so as to prevent unnecessary stress on the compressor motor. When turning off the compressor for extended periods, close the blue handled valve on the upper left side of the tank.

The carriage also requires inspection. The spring, rod, and linear bearing assembly on the dynamic carriage should have the springs connected and the rods should be free of any dirt or corrosion (see figure 6). The tires on the dynamic carriage should be inflated to 90

psi, the full capacity of the compressor. There are two pair of tires, one pair fore and one aft. The inflation valves for the tires are accessed by removing the half-moon face plates on the hub of each tire. There are two plates per tire, and the plate which bulges slightly is the one to be removed. Caution should be used when inflating these tires; looking away from the tire as it is inflated, while keeping faces out of the plane of the tire is strongly advised. After the tire has been inflated to the correct pressure, it is important to put the face plate back. For each pair of tires there are a set of hard wheel stops; there must be clearance between the hard wheel and the track on which the tires ride (see figure 4).

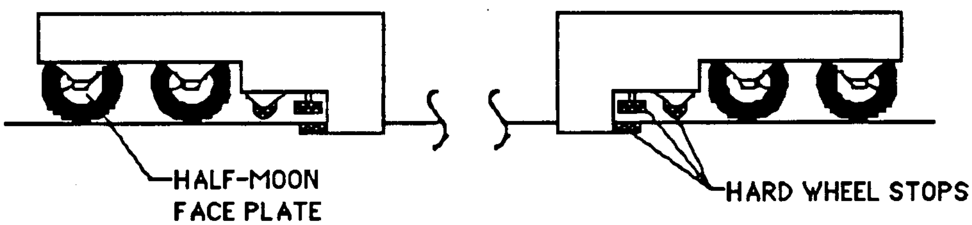


FIGURE 4

The vents on the northwest side of the longtrack should also checked for large obstructions. .hese vents cool the track's generators and can be visually inspected from the machine shop windows. Switches 38 and 39, located on circuit breaker light panel #1 and switches 13, 15, 16, and 17, on circuit breaker light panel #2 must be on before turning on the control console or generator. The carriage hydraulic drive must be off (hydraulic drive on/off, red button in, see figure 5) and the three toggle switches (pressure bypass, yoke center, and servo) on the hydraulic drive control box (see figure 6) must also be off. The 60 Hz power supply on the carriage must be unplugged as well.

Power-up and Operation:

Power may now be supplied to the rails. Power must first be supplied to the control console by pushing the red "CONSOLE PWR" switch, located on the console. The constant frequency generator can be turned on by pressing the "START" button located under the left front ledge of the console. The "Generator" meter in the blue "CARRIAGE TRACK" section of the console should read approximately 125 volts. The "TRACK ON" button is next pressed and held until the relay "clicks" on. It will take approximately 30 seconds for the relay

to engage. The second red light from the right, above the console window, should now be on. In the "CARRIAGE TRACK" section, the "VOLTS" meter should indicate approximately 118 volts and the "CURRENT" meter should register less than 20 amps. After one minute the power supplies should all have stabilized and the "Christmas tree" colored lights on the carriage power supply should be on (see figure 6).

With power on the rails, the hydraulic drive may now be brought on-line. First the carriage pneumatic system must be intially brought up to pressure by turning on the carriage compressor. The pneumatic pressure gauges and the compressor on/off switch are located on the front part of the hydraulic drive system. The carriage compressor gauge should be reading approximately 90 psi when the compressor stops. This gauge is located on the opposite side of the hydraulic drive system. After making sure that the three switches on the hydraulic drive control box are still off, the power-up of the hydraulic drive may begin. It is advisable to wear ear protection when operating the hydraulic drive. <u>While standing clear of the carriage</u>, and with one hand on the hydraulic drive "on" button and the other on the "off" button, turn on the drive system and then off again quickly. The carriage should have lurched in one direction. This on/off cycle should be repeated until the carriage no longer moves when the drive is turned on. When the carriage does not move, leave the drive on. If more than three cycles are required, Ted Griffith should be notified. Once the hydraulic drive system is running, the pinion gear lubrication system should be 600 psi and the lubrication oil must be flowing in the sight tube. The lubrication pressure gauge is located near the drive's on/off buttons. The hydraulic drive should be allowed approximately 30 minutes to warm-up. During this time, it is a good idea to make sure that the break and release lights are in their proper locations, and on. The break lights are the lowest set of bulbs. If any need replacing, use at least 60 watt bulbs, 100 watts being nominal.

Once the hydraulic drive is warm, the oil and air gauges must be checked. The air and oil gauges should be reading between 20 and 30 psi, and it is important that these gauges read the same value. If the oil pressure is lower than the air pressure, oil must be added to the system. To accomplish this task, the hydraulic drive and carriage air compressor are first turned off, and the air pressure must then be purged to zero. The oil supply is located on the track floor and its air pressure must first be turned on at the tank. The feed hose should

then be cleared of any air and debris by disconnecting the hose from its hold connection and pointing the end of the hose into a pail. Then, by turning on and off the supply valve located at the far end of the platform, the hose can be cleared. With the valve off, the hose can then be connected to the carriage fitting. After the hook-up the supply valve should be turned on, followed by the feed valve on the carriage, which must be closed again after a few seconds. The pneumatics can then be brought up to pressure with the house air supply hose. This proccess is repeated until the gauges read the same value. If the oil pressure is too high, oil must be bled from the system, using the four bleeder valves located by the two pressure gauges. While the system is running, each of these valves must be bled one at a time, even if the oil pressure is nominal. A continuous stream of oil should be seen before closing the opened valve and bleeding the next. The water trap should be drained and the bottom pan should also be cleaned of oil so that abnormal leakage may be easily recognized. The air and oil trap accessed from the track floor should also be bled periodically (see figure 6). To ensure a dry air supply during winter operation a granular dessicant must be filled into the dessicant canister, located next to the water trap. An outlay displaying component locations can be found in figure 5.

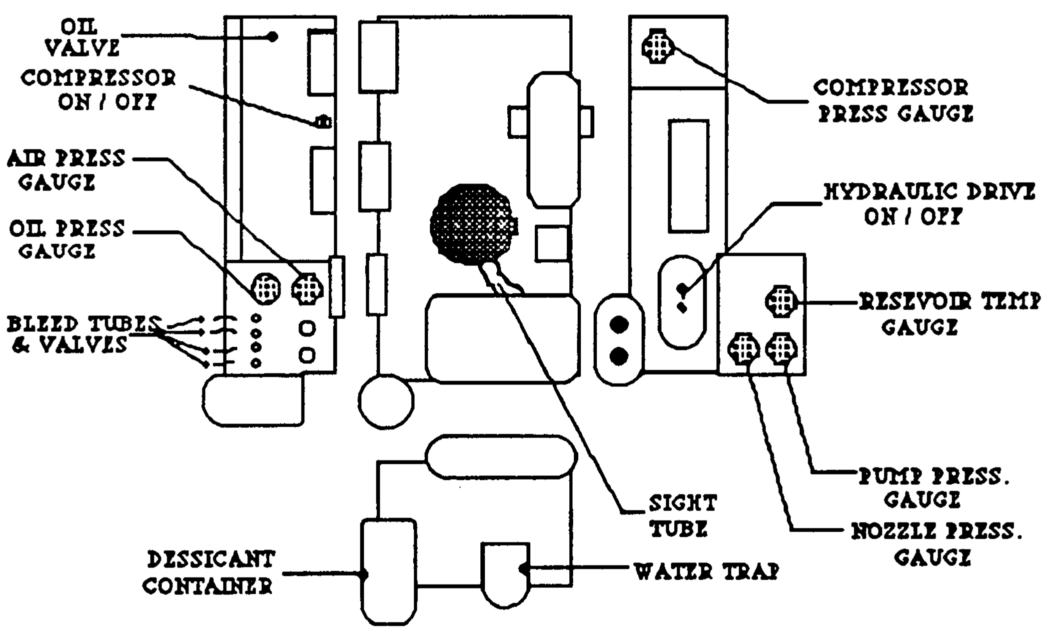


FIGURE 5

After the hydraulic drive is operating, the velocity servo can be checked out. The hydraulic drive control box should be manually positioned between two track poles. Its location and the switches associated with it can be found in figure 6. The green "RESET" button is pushed first and should light up. Any remaining lights on should be turned off. The "Fwd/Bkwd" should be pushed so that "Fwd" is lit. The V_0 pot is next set to read 2.2. With one person operating the hydraulic drive control box, and another ready to hit the track-kill button in case of a carriage runaway, the following zero velocity check should be performed. This check is performed by turning on the "yoke center" switch, the "servo" switch, and finally, the "press-bypass" switch. Upon throwing the "press-bypass" switch, the carriage will generally begin translating in the forward direction. Turning off this switch will stop the carriage. The operator of the hydraulic drive control box may wish to zero carriage velocity in one of two ways. In the event that carriage velocity is fast, the first attempt should be to stop the carriage by turning off the "press-bypass" switch. Based on the direction of motion of the carriage, the V_0 pot should then be readjusted. If the carriage moves forward the pot should be adjusted slightly down and similarly, if the carriage moves backwards the pot should be adjusted up. When carriage velocity is small, the operator may walk with the carriage, and zero its velocity by merely tuning the V_0 pot as mentioned previously. If this method is used the operator must be cautious of tripping and pole avoidance. This method should only be used when carriage velocities are small. Upon successful completion of achieving zero carriage velocity the V_0 pot value should be recorded. The three switches should then be turned off in reverse order from above. If the carriage escapes from the person operating the hydraulic drive control box, the track-kill button should be pushed by the second person. In the event of a kill, all switches on the hydraulic drive control box should be turned off. The carriage will have to be manually pushed back to the platform in order to turn off the hydraulic drive and carriage compressor. Once these switches are off, the procedure for supplying power to the rails should be followed as before.

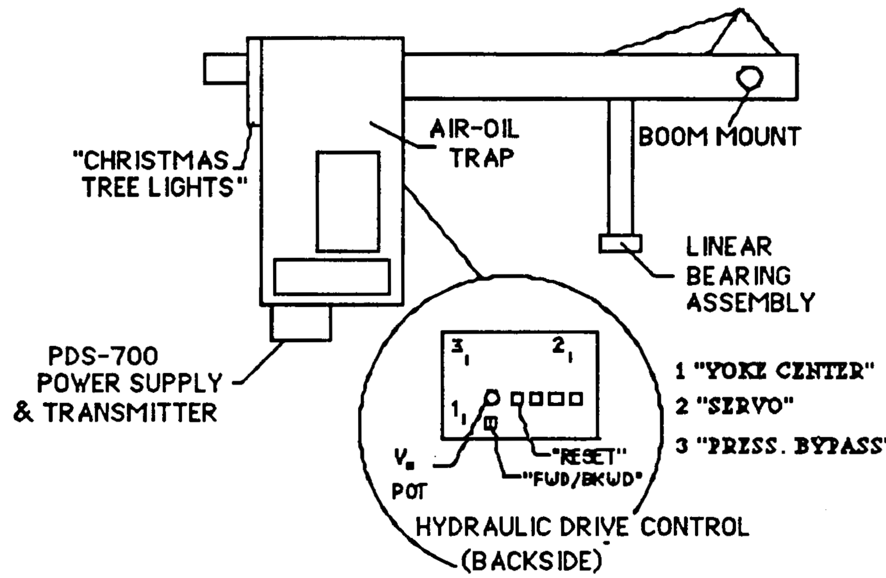


FIGURE 6

The carriage is ready to be operated in constant velocity mode, after the velocity servo has been zeroed. The V_0 pot setting commands a hydraulic pump displacement. Note that velocity is not fed back to the system, V_0 is simply a command input corresponding to a pump yoke position. A feedback controller is used to keep yoke position constant. As the hydraulic fluid heats up and/or the carriage load changes, the velocity for a specific pot setting will vary from run to run, however the velocity during a particular run will be relatively constant. Carriage velocity is approximately 1.6 ft/s per unit increment of the V_0 pot. If any fluctuations in carriage velocity occur on a given run, its cause should be identified and the problem corrected.

Knowing the zero velocity setting on servo pot, it is possible to run the carriage at a chosen velocity. With all three switches on the hydraulic drive control box off, the chosen velocity can be commanded using the V_0 pot. Push the green "RESET" button and cycle the "Fwd/Bkwd" button so that "Fwd" is lit. Release functions can be engaged or disengaged by toggling the "RELEASE" button, located near the "RESET" button. Release functions will occur when the carriage passes any release lights. Carriage motion at the chosen velocity can be initiated by turning on the "yoke center" , "servo", and "press-bypass" switches in sequence. Once the "press-bypass" switch is thrown the carriage will accelarate at approximately 6 ft/s^2 to the chosen velocity. It will maintain that velocity until it reaches

a set of brakelights, at which point it will deccelerate at roughly 5 ft/s^2 to a "backward creep" mode. This mode is identical to carriage motion with only the "press-bypass" switch on. After a time lapse determined by the timer on the hydraulic drive control box, the carriage will automatically switch into backward velocity mode. In backward velocity, the brake light will not stop the carriage and thus the carriage will return to the backward brake cam which will return the carriage to "backward creep" mode. At this point, the three switches should be turned off in reverse order; "press-bypass" off, "servo" off, and "yoke" off.

At all times users must be alert to any signs of unusual behavior of the carriage and drive system. Make sure people and objects are not in the path of the carriage or any attached booms and models. Never expose people to any operating rotor, always use shields to inspect operating models. Always have a person near one of the track-kill buttons, and arrange for cues to inform that person if a shut-down is needed. All track operations must be monitored continuously.

EXPERIMENTAL PROCEDURE:

Steep Descent:

The regime of steep descent in rotorcraft has not yet been fully understood. It has been shown to be a very hazardous flight envelope and thus should be explored in more detail. A hingless rotor has been set up at this facility to study this regime. Flow visualization of this rotor in steep descent has been performed. To further explore steep descent with this rotor, data will be taken using the newly installed high-speed digital data aquistion system. The resulting data will be used to gain further insight into the problem of steep descent encountered by rotorcraft.

Strain Gauge Calibration:

The TASK strain gauge balance has 12 elements, making it possible to measure force and moments on all axes. Only ten of these elements are currently used, with the remaining two being unusable due to open bridges. The balance is documented with circuit diagrams.[6] Calibration was accomplished after mounting the balance

horizontally on track pole #17, positive X pointing north (see figure 7).

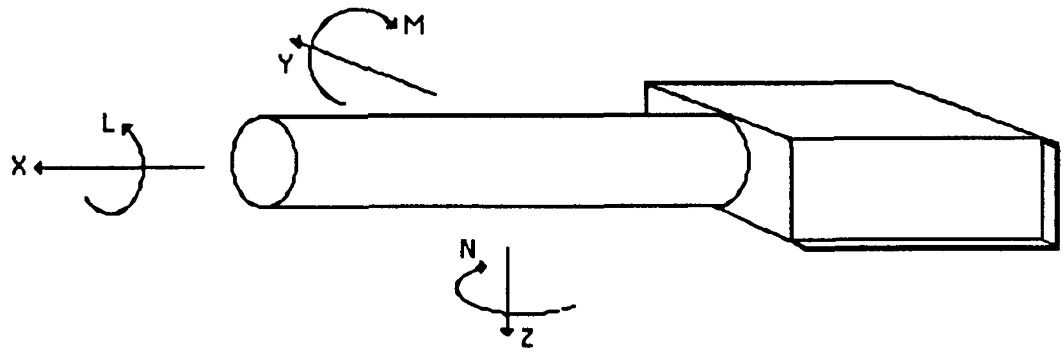


FIGURE 7

Before balance calibration began, the strain gauge amplifiers were independently calibrated. Gains were set at 333, which is determined by resistor R12 in each amplifier network. This gain can adjusted slightly by a corresponding trim pot. (see reference 1). Under zero load the amplifiers were individually balanced using a digital voltmeter to an output within 10 milivolts of zero. A calibration body was used as an accurate reference in loading the balance. Loads were applied to all axes, a compound loading condition was used to calibrate the moments. Data values for each load were determined by sampling 30 data points on each of the six channels, which represented the three forces and three moments. Any spikes in the data were then removed and an average of the remaining data was determined. Six different loading conditions were used and a total of 15 loads were used for each condition.

The vector of forces and moments acting on the strain gauge balance is defined as:

$$\{y\}^T = \{ X, L, M, Z, Y, N \}$$

with forces expressed in lbs and moments in ft-lbs. The vector of data is defined as:

$$\{x\}^T = \{ c1, c2, c3, c4, c5, c6 \}$$

where the data channel readings are expressed in counts. The maximum number of counts is 1000, with available resolution of one count. The relationship between these quantities is expressed as:

$$\{y\} = H \{x\}$$

where the matrix H is determined through calibration of the strain gauge instrumentation system. Individual loads are placed on the strain gauge balance and from channel readings the elements in the matrix H are determined through a least-squares procedure.

Given a set of differenced loads, $y^T = (y-y_0)^T$, and a set of differenced data, $x^T = (x-x_0)^T$, a relation can be formed as follows;

$$y^T = x^T H^T$$

where y and x have dimension 6x1. This relation allows loads to be determined from a given set of data. With the given calibration data, H was determined by a least-squares fit from the following relation;

$$H^T = [(x^T)^T x^T]^{-1} [(x^T)^T y^T]$$

where x^T and y^T have the dimension of the number of data points by the number of channels, which for the above case is 83 x 6.

$$H = \begin{bmatrix} 0.898 & 2.27E-3 & 1.14E-3 & 2.23E-3 & -7.14E-3 & -0.0133 \\ -1.07E-4 & 0.0297 & -6.13E-5 & -1.41E-3 & -1.16E-3 & -2.59E-3 \\ -3.24E-3 & -5.49E-4 & 0.0763 & 2.71E-4 & -1.00E-3 & 3.76E-3 \\ 3.29E-4 & -3.53E-4 & -2.19E-3 & 0.316 & -3.29E-3 & -0.0132 \\ 4.72E-4 & -7.26E-4 & -2.00E-3 & -8.03E-4 & 0.202 & 0.627 \\ -8.7E-5 & 1.71E-4 & 1.23E-4 & 1.71E-4 & -0.0400 & 0.129 \end{bmatrix}$$

This H matrix was then used on the existing data to calculate predicted loads. Plots of the predicted loads versus the actual loads, including cross terms from the unloaded channels, are given in figures 8-13. Calibration data and this matrix can be found in the APL workspace CALDATA.

As can be seen, the dominant elements are the diagonal ones, except in the case of Y, N. The interpretation of the diagonal elements is as follows:

$$h11 = 0.0898 \text{ lbs / count}$$

A reading of 1000 counts in channel 1 thus corresponds to an axial force of 89.8 lbs, which represents the total range of the balance. Since the axial force is in general quite a bit smaller than this value, it would be desirable to increase the sensitivity in this channel. Off diagonal terms are due to coupling in the balance, thus, non-zero h21 indicates that the reading in channel 2 corresponds to some axial (X) force.

Sting Mount and Rotor Operation:

The calibrated strain gauge balance was mounted to the rotor using the standard body axis coordinate system. Positive model translation is in the southern direction. It is important that power be supplied to the Task balance at all times to keep the gauges warm and free of moisture.

Model power is supplied by the variable frequency generator located in its own room on the northwest side of the longtrack. The control panel for this generator is located next to it on the south side. Rotor RPM is controlled by varying the frequency of this generator. This function is performed by the frequency adjust potentiometer located on the control panel and can be remotely controlled by the red and green buttons in the yellow "MODEL TRACK" section of the control room console. Before bringing up the variable frequency generator, it is important that the frequency adjust potentiometer is fully counter-clockwise against its stop. This task must be performed at the control panel. A small relay will click just before you reach the stop. Check for that click to verify that the pot is fully counter-clockwise. "CONTROL POWER" is turned on first which will produce a humming noise. The user should not proceed until the hum generated by the control panel has reached equilibrium. The "PRIME MOVER" is turned on next. There will two audible clicks after

it has been turned on. The relays are located in the gray cabinet to the left of the control panel; a slight delay occurs between clicks, and the "DC POWER SYSTEM" should not be turned on before the second click. After turning on the DC Power System the "ALTERNATOR OUTPUT CONTACTOR " can be turned on, thus completing the variable frequency generator power-up. The three controls labeled: "EXT. FREQ.", "1V/C 1/2V/C", and "VOLTS ADJ." must not be altered from their preset values.

All rotor operations are performed from the control room. With the variable frequecy generator on-line and the console in the control room on, model power may be supplied to the rails. In the gray "VARIABLE FREQUENCY GENERATOR" section on the console, there are four red lights. Each one corresponds to the on/off condition of the buttons on the variable frequency generator's control panel. They should all be on. The white "TRACK ON" button in the yellow "MODEL TRACK" section is pushed to supply power to the rails. This button should begin to flash and the blue lights on the track should flash as well. The left-most red light above the console should also be on. To make viewing the rotor easier, lights in the control room should be off while operating the rotor. The conrol room door should be initially left open as rotor rpm is increased so that the relay which puts power on the rails may be heard engaging. As the red button is pushed the frequency adjust potentiometer will come off its stop and thus release its relay. This relay will in turn engage the larger relay. It is this second relay which can be heard from the control room. Continuing to push the red button will gradually increase rotor rpm; however there is a substantial lag between command and response, so rotor rpm must be brought up slowly. Hold the red button for only short periods of time and wait for the rotor to come to speed before proceeding. The green button will correspondingly decrease rotor rpm and should be operated in a similar fashion, being cautious of not decreasing rotor rpm too quickly. The rotor must be viewed at all times during its operation and should not be run in excess of 30 minutes without checking motor temperature. At nominal operation the "AC VOLTS" meter in the "MODEL TRACK" section should read 125 volts, and the "FREQENCY" meter in the "VARIABLE FREQUENCY GENERATOR" section should be between 300 and 400 Hertz. Rotor rpm can be measured using the strobe. Powering down the variable frequency generator must be performed in reverse order to bringing it on-line.

Collected and Processed Data:

A static test run of the rotor was made and data was collected using both the programs dma2page and dma2file. Sampling rates were set at 500 hertz. Data was also displayed using SCOPE. Although this data is not very interesting it did result in proof of concept of the data system. Thrust was calculated based on theory and this value compared well with the measured value. A one per rev in roll was also found and the frequency extracted from it matched well with the rotor rpm measured with the strobe. Data plots and spectral plots are presented in figures 13-19 showing the measured rotor forces and moments in a steady hover in the balance axis system. These axes are located 13.82 inches below the rotor hub on the shaft, as shown in figure 21 from reference 7.

Steady falues are:

Xo = 0.0 lbs

Yo = -2.2 lbs (with 1 per rev oscillation)

Zo = -8.7 lbs

Lo = 0.8 ft-lbs (with 1 per rev osc.)

Mo = 0.6 ft-lbs

No = 2.6 ft-lbs (rotor torque)

Comparing the steady thrust and power (No x rotor speed) gives a figure of merit of 0.46, a reasonable value. However, the rotor side force, Y, does not seem physically reasonable. A steady Y force of this magnitude would produce a rolling moment about the balance center that would indicate a large rolling moment on the hub, and a large lateral misalignment of the rotor.

It is important to realize that the significance of the presented data is to merely show that data may be acquired with reasonable accuracy. Variations in this data may be due to noise or vibrations due to an untuned rotor. It is also important to keep in mind that

the data is discete and the gains used in collecting the data are currently set to handle large load variations.

CONCLUSIONS:

The data system is installed and calibrated for steep-descent experiments. A static test of the rotor with the PDS-700 and the PAD-400 hardwired together was used to test hardware and software. Upon installation of the radio link these experiments can proceed. This document presents a basic overview for the capabilities and operating guidelines for the Princeton Dynamic Model Track. Due to the amount of documented software, it is presented in a separately bound appendix.

SUGGESTIONS FOR FUTURE WORK:

It is imperative that the radio link for this data system be installed and tested. Upon installation of the radio link a similar static test to the one above should be performed to test for data validity. Additional software to meet specific needs can always be added with the ground work having been laid down. The addition of expandable memory for the AT would help alleviate some the software bugs and make larger data transfers possible. The carriage has been equipped with a small DC generator for measuring carriage velocity. This piece of hardware should be calibrated and tied to one of the analog inputs on the PDS-700. To enhance the capabilities of the carriage, the analog computer can be replaced by a small on board digital computer. With digital computing power available, digital control laws for various aircraft could also be checked out using the semi free-flight capabilities of the carriage.

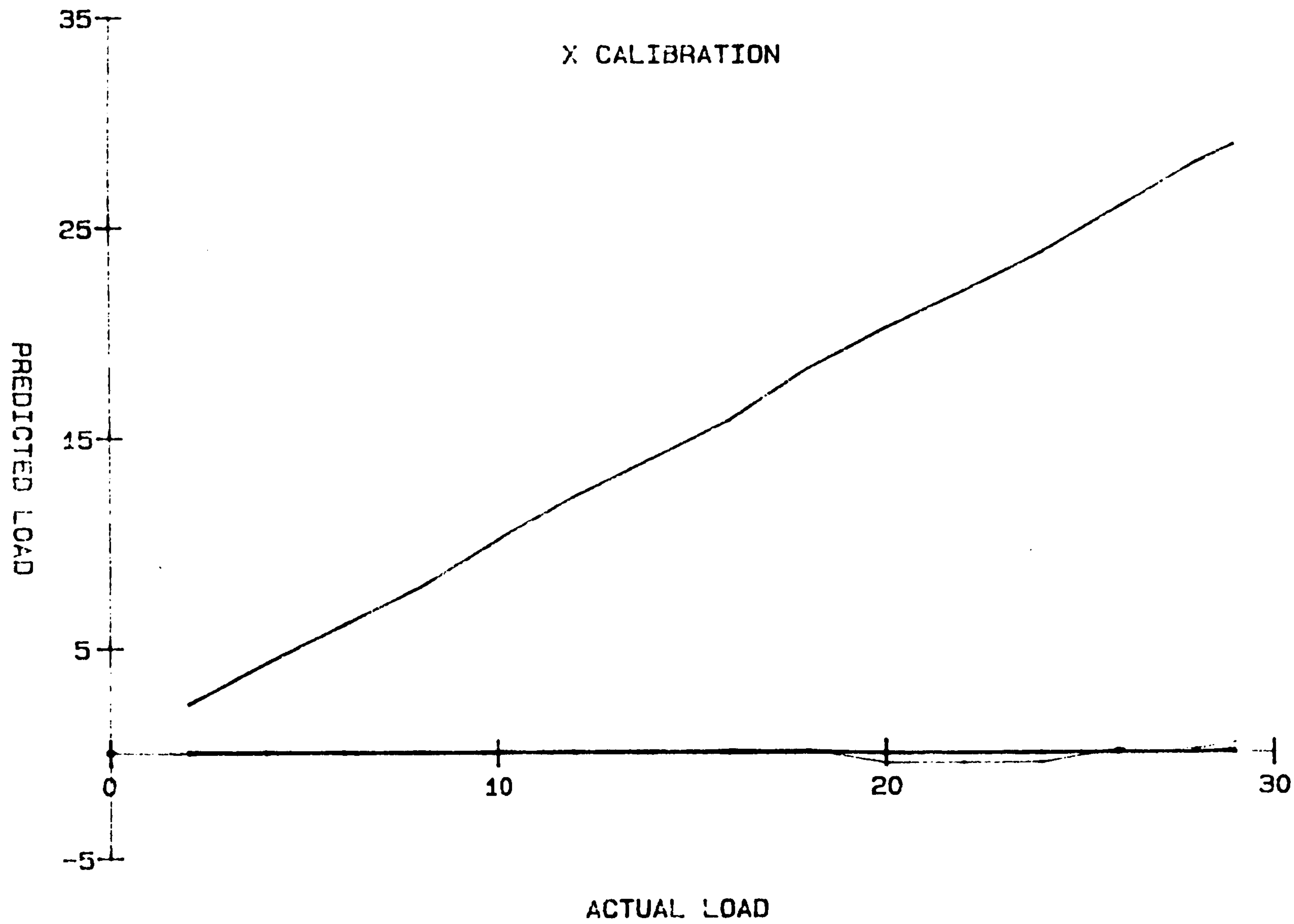


FIGURE 8 - PLOT OF AXIAL FORCE PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

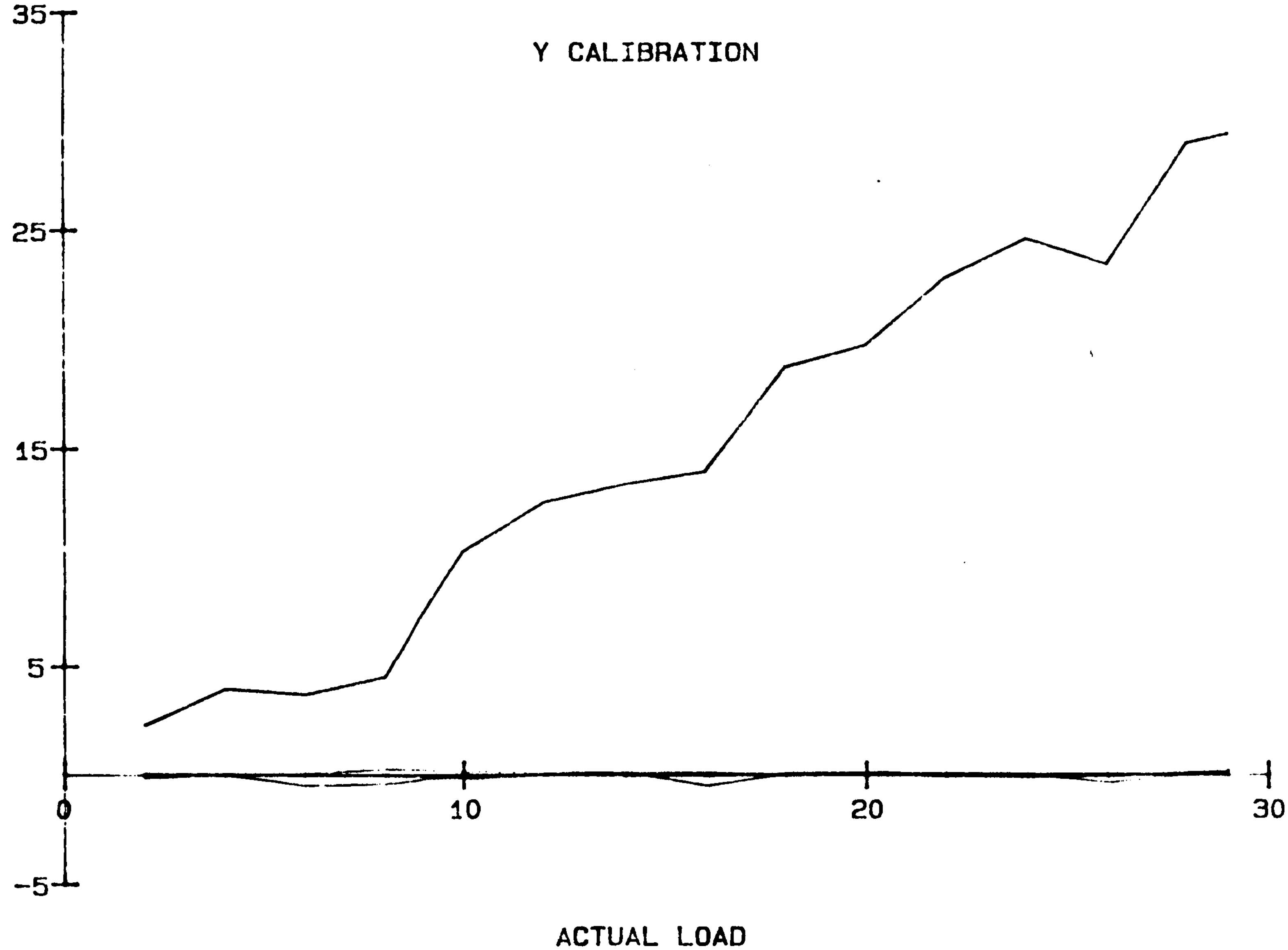


FIGURE 9 - PLOT OF SIDE FORCE PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

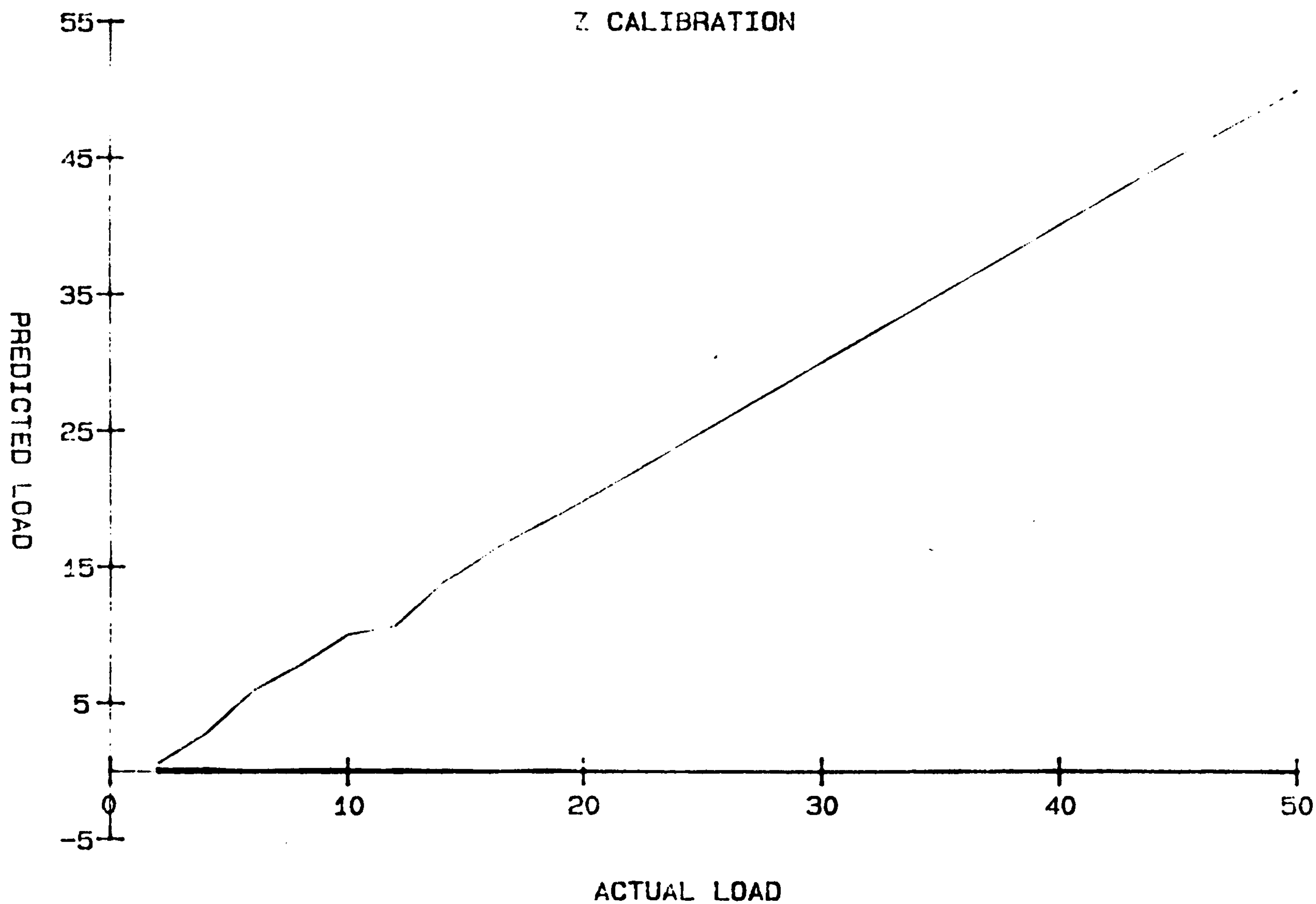


FIGURE 10 - PLOT OF VERTICAL FORCE PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

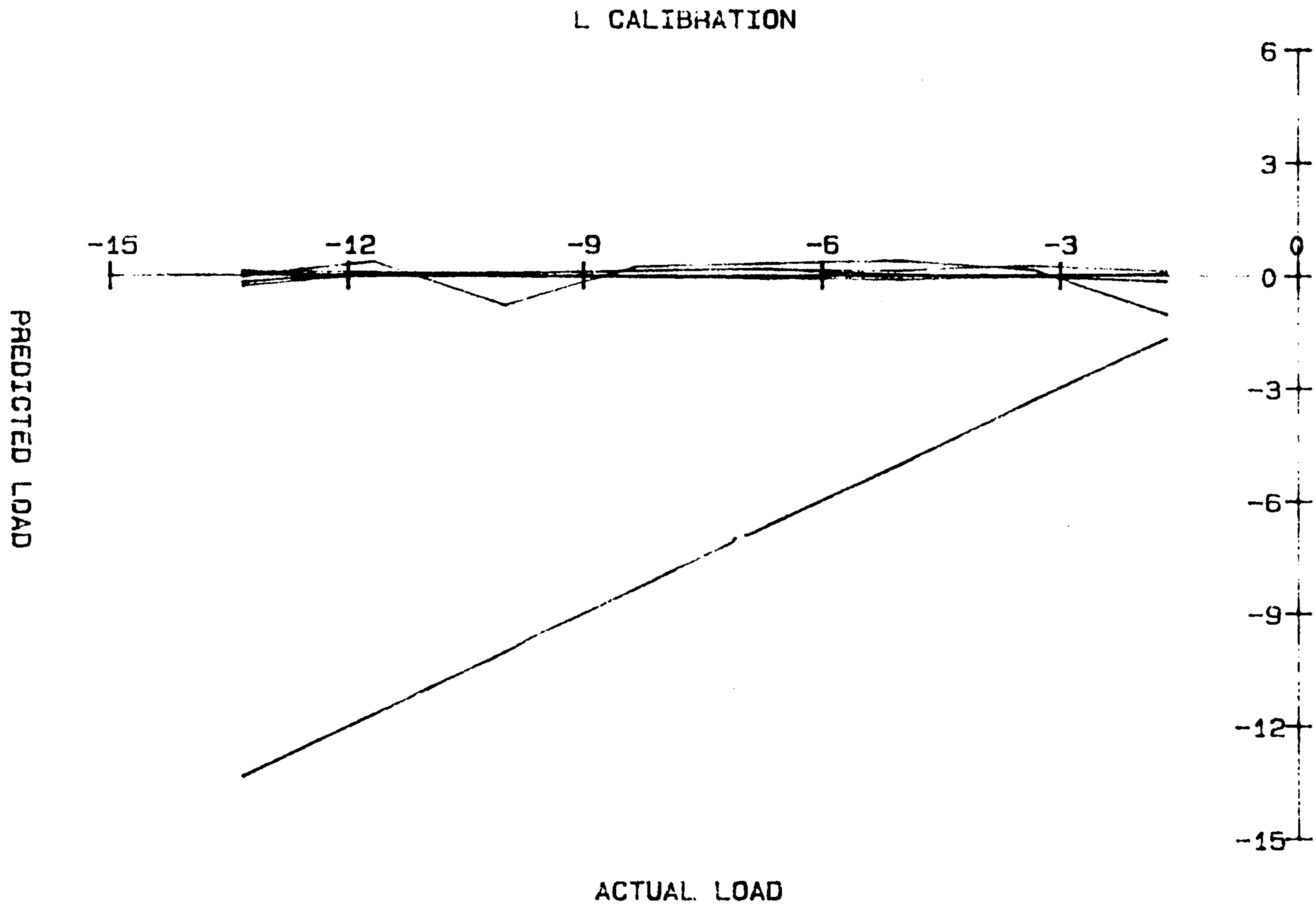


FIGURE 11 - PLOT OF ROLL MOMENT PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

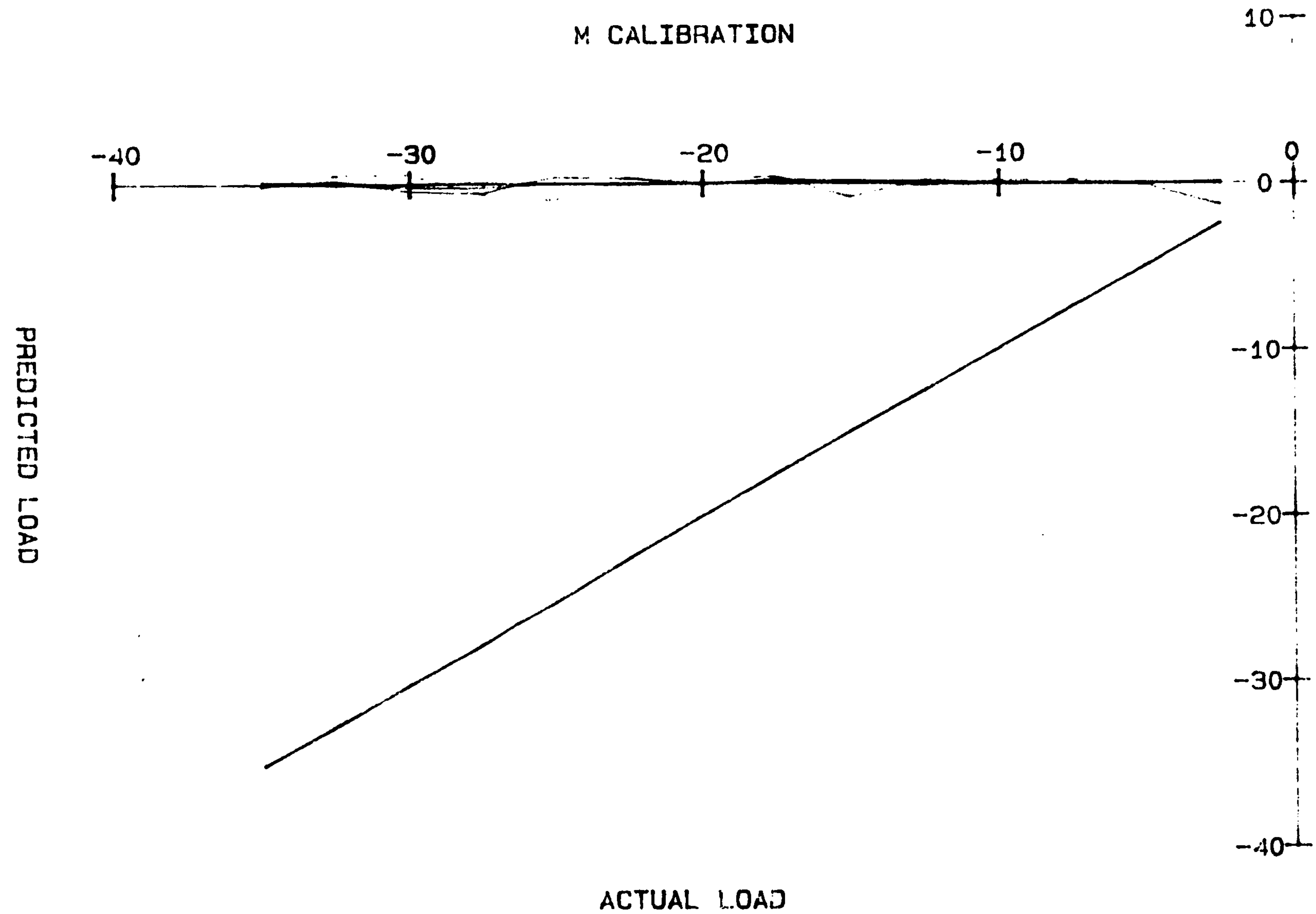


FIGURE 12 - PLOT OF PITCH MOMENT PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

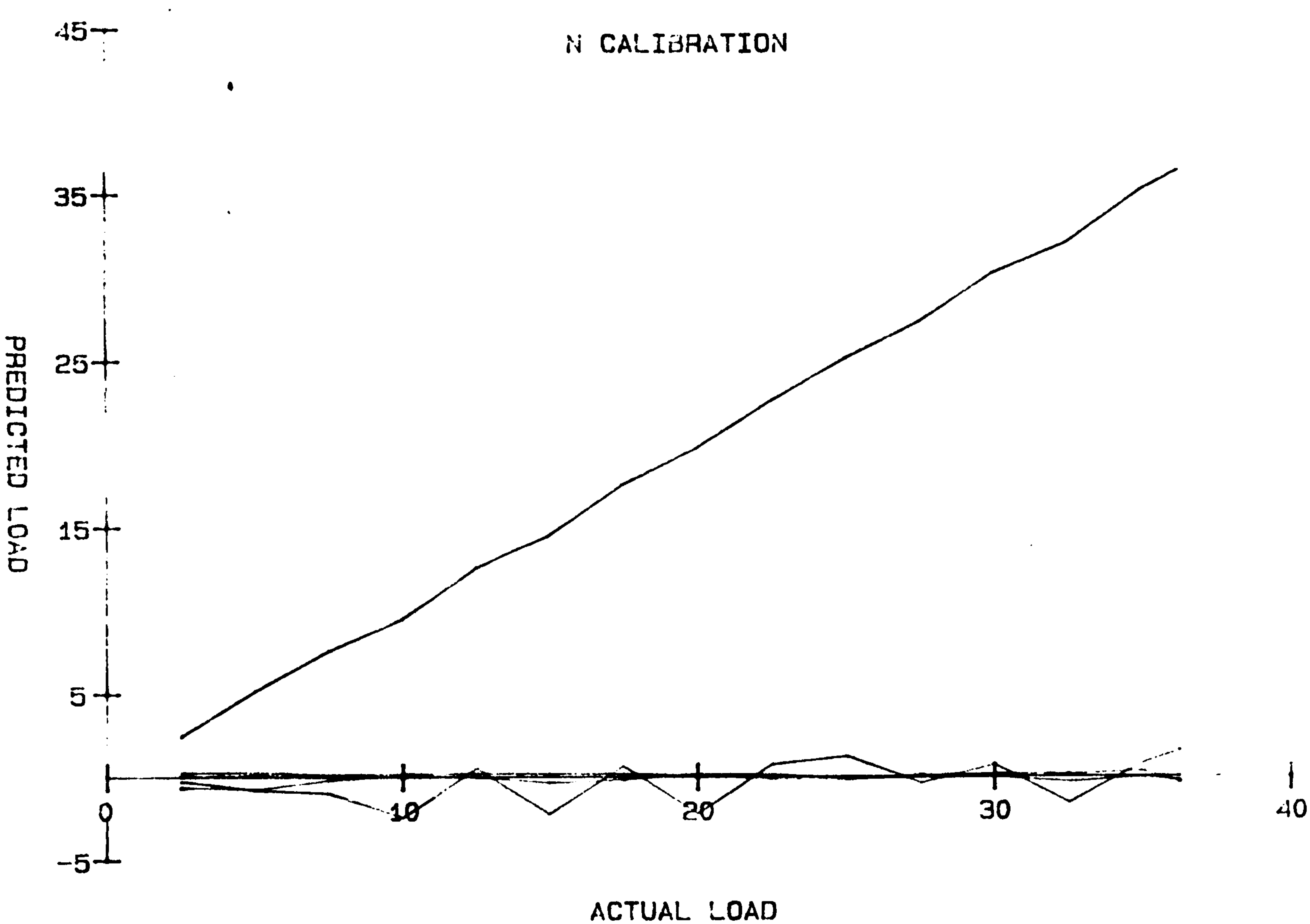


FIGURE 13 - PLOT OF YAW MOMENT PREDICTED LOADS VERSUS ACTUAL LOADS, INCLUDING PLOTS OF CROSS TERMS FROM OTHER CHANNELS.

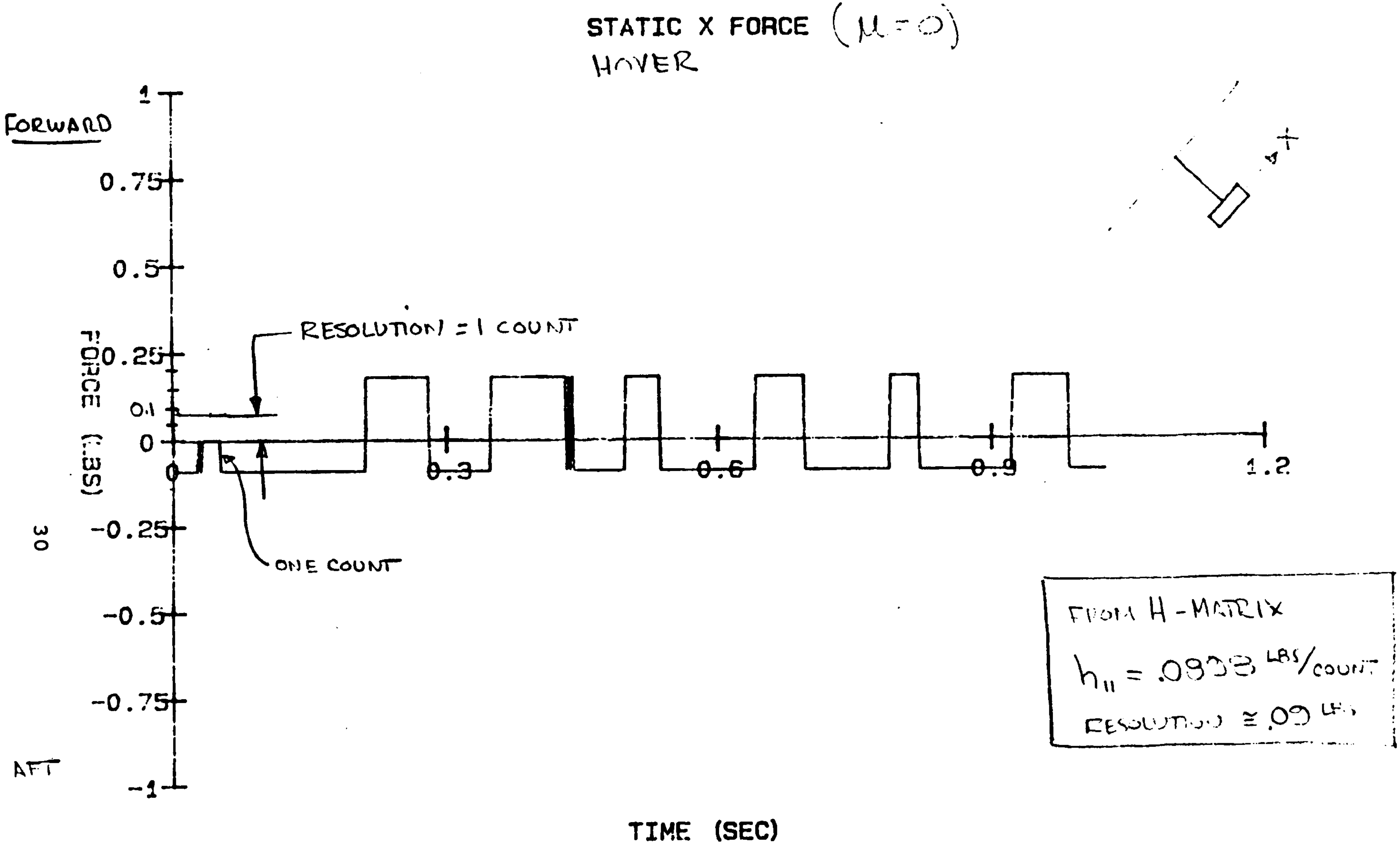


FIGURE 14 - PLOT OF AXIAL FORCE DATA FROM STATIC ROTOR TEST

DIAGONAL TERM [.0898 LBS/COUNT]

AVERAGE VALUE ≈ 0 LBS

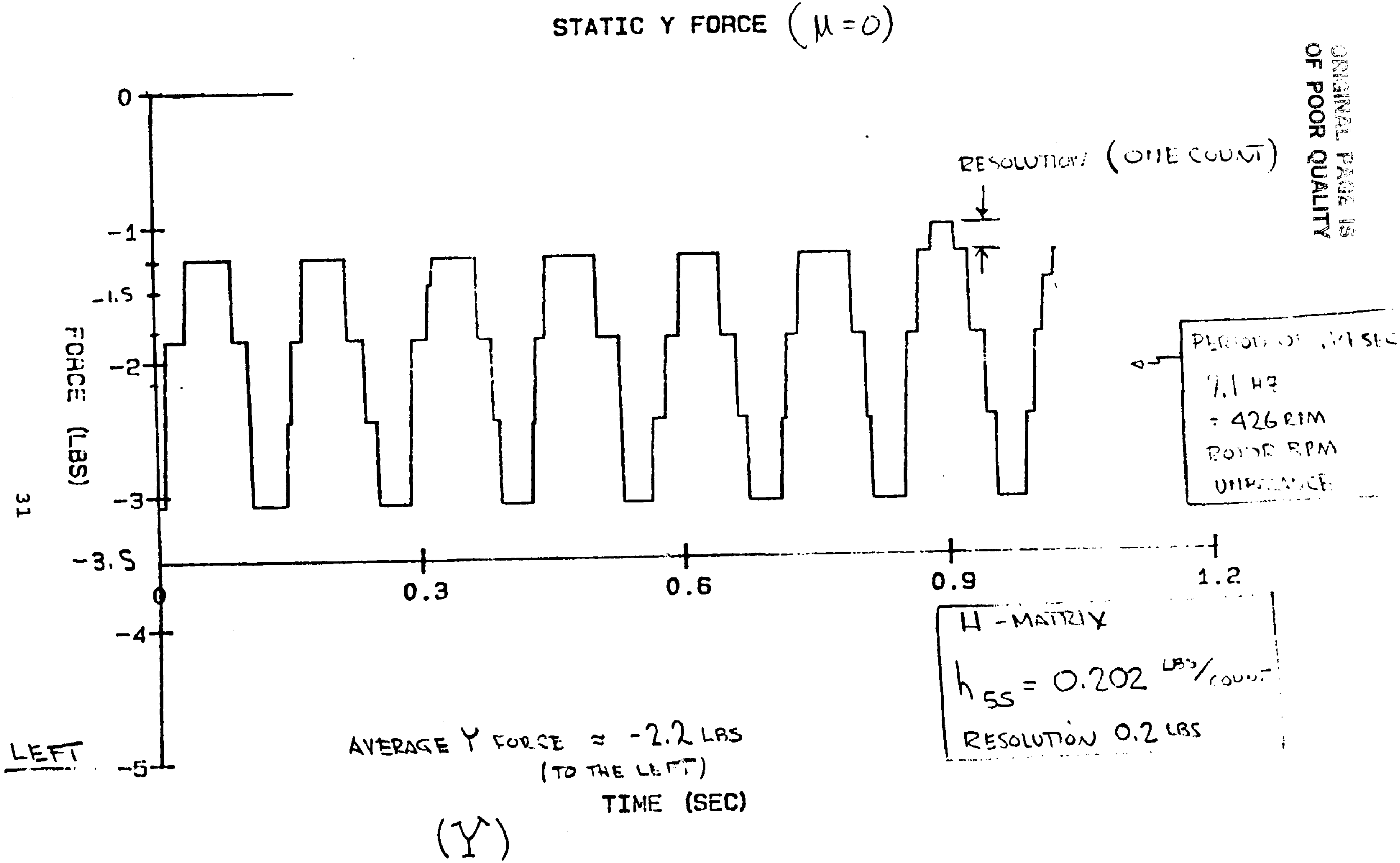
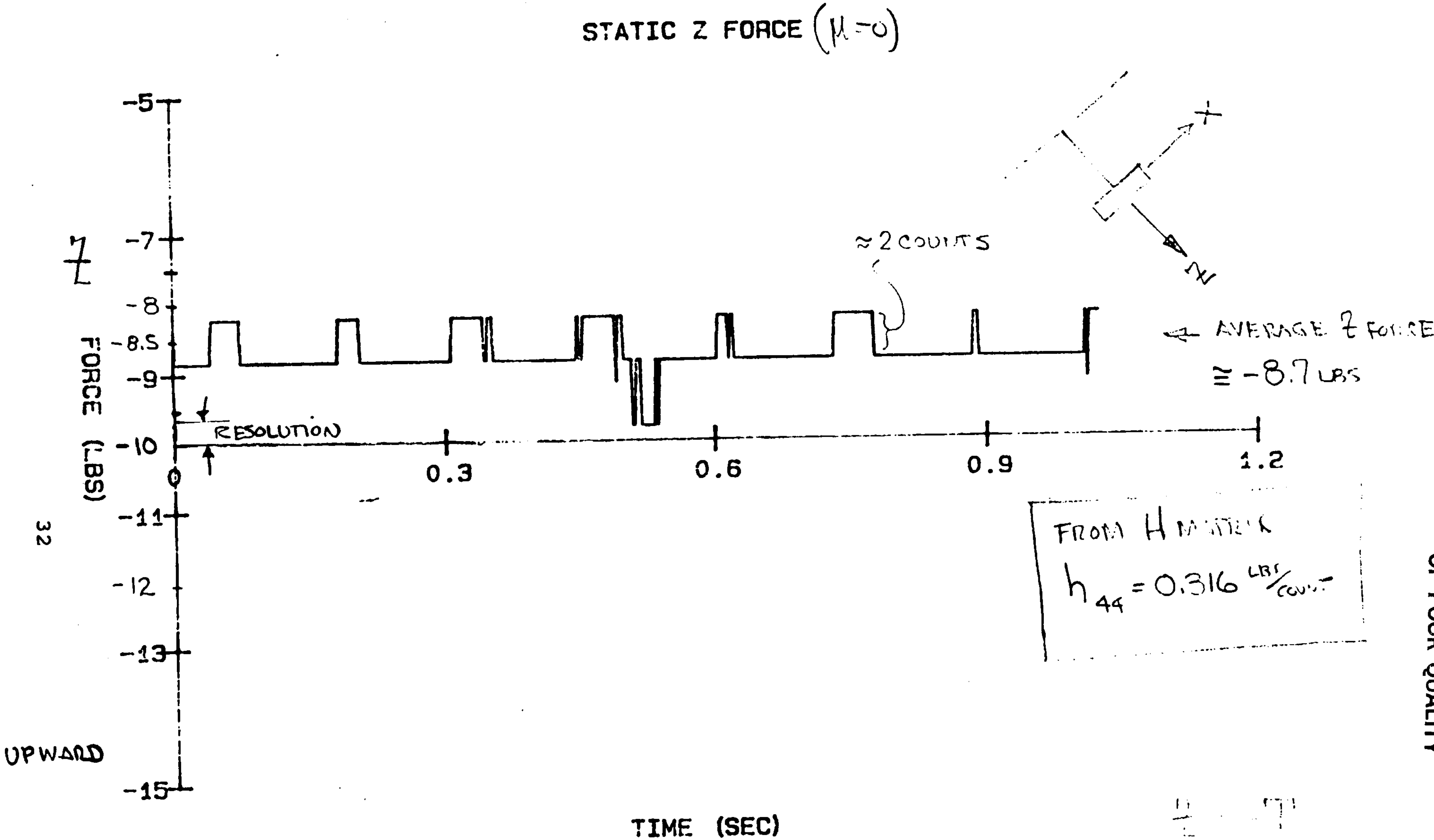
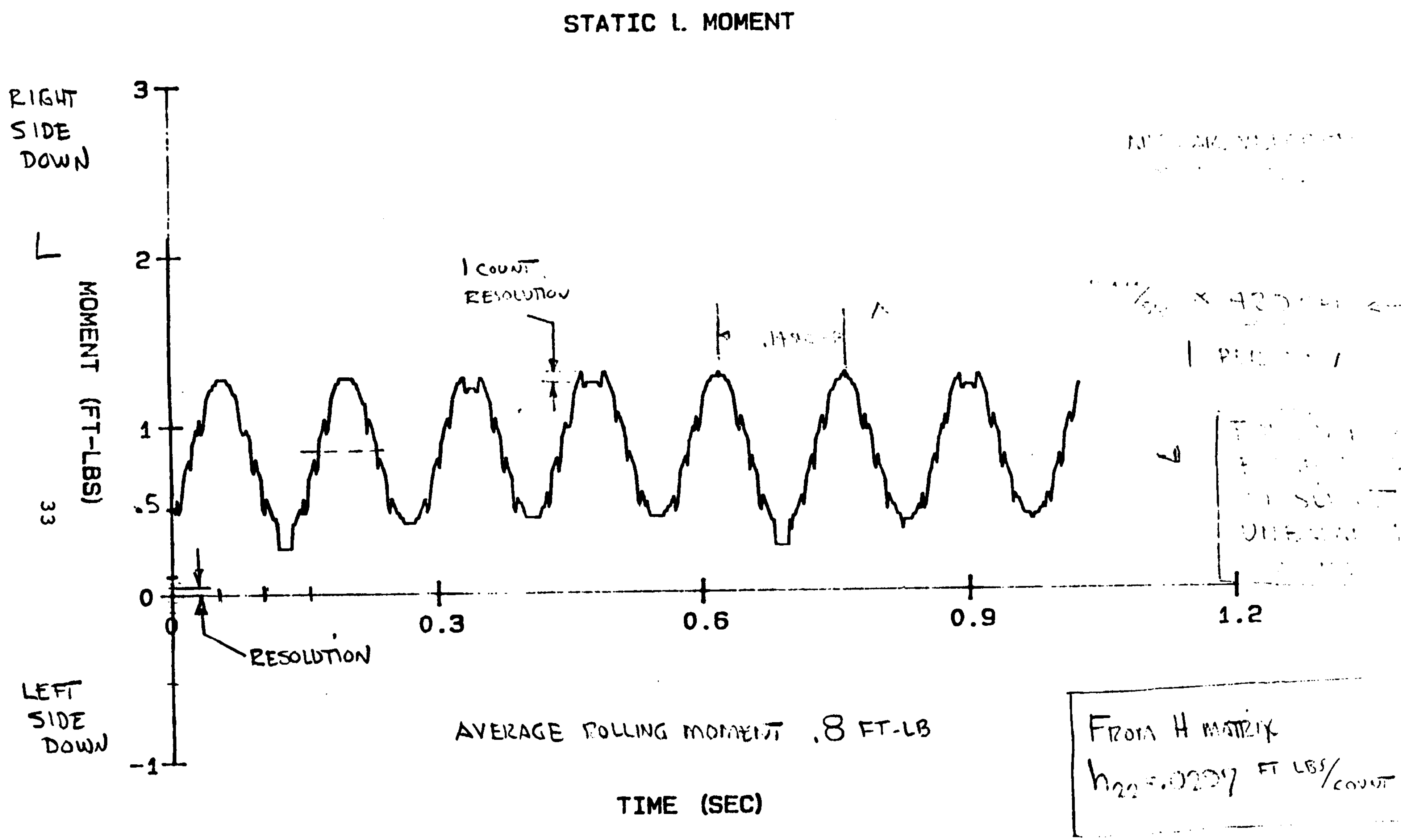


FIGURE 15 - PLOT OF SIDE FORCE DATA FROM STATIC ROTOR TEST

(DIAGONAL TERM 0.202 LBS/COUNT)



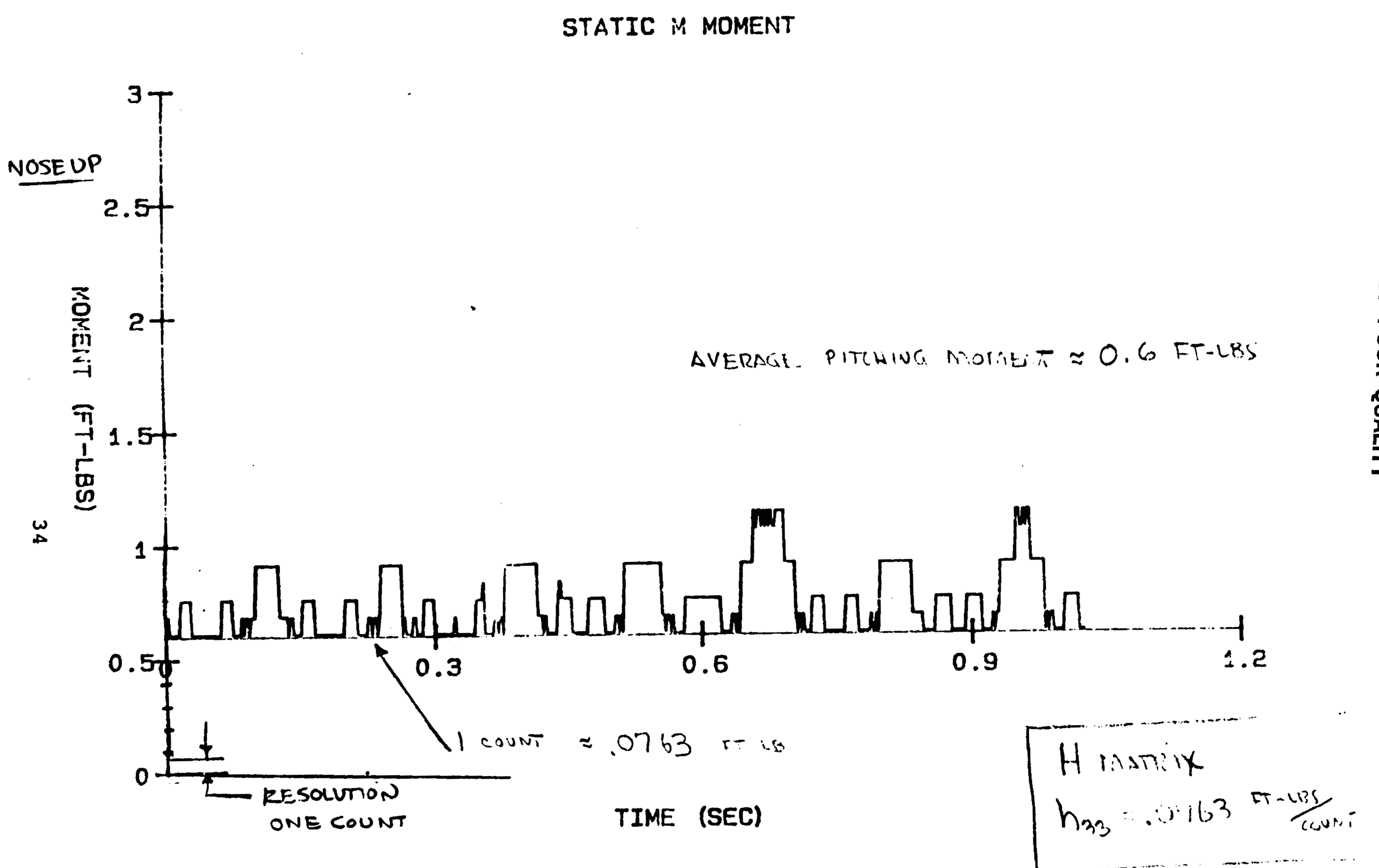
(Z)
FIGURE 16 - PLOT OF VERTICAL FORCE DATA FROM STATIC ROTOR TEST
(DIAGONAL TERM 0.316 LBS/COUNT)



(L)

FIGURE 17 - PLOT OF ROLL MOMENT DATA FROM STATIC ROTOR TEST

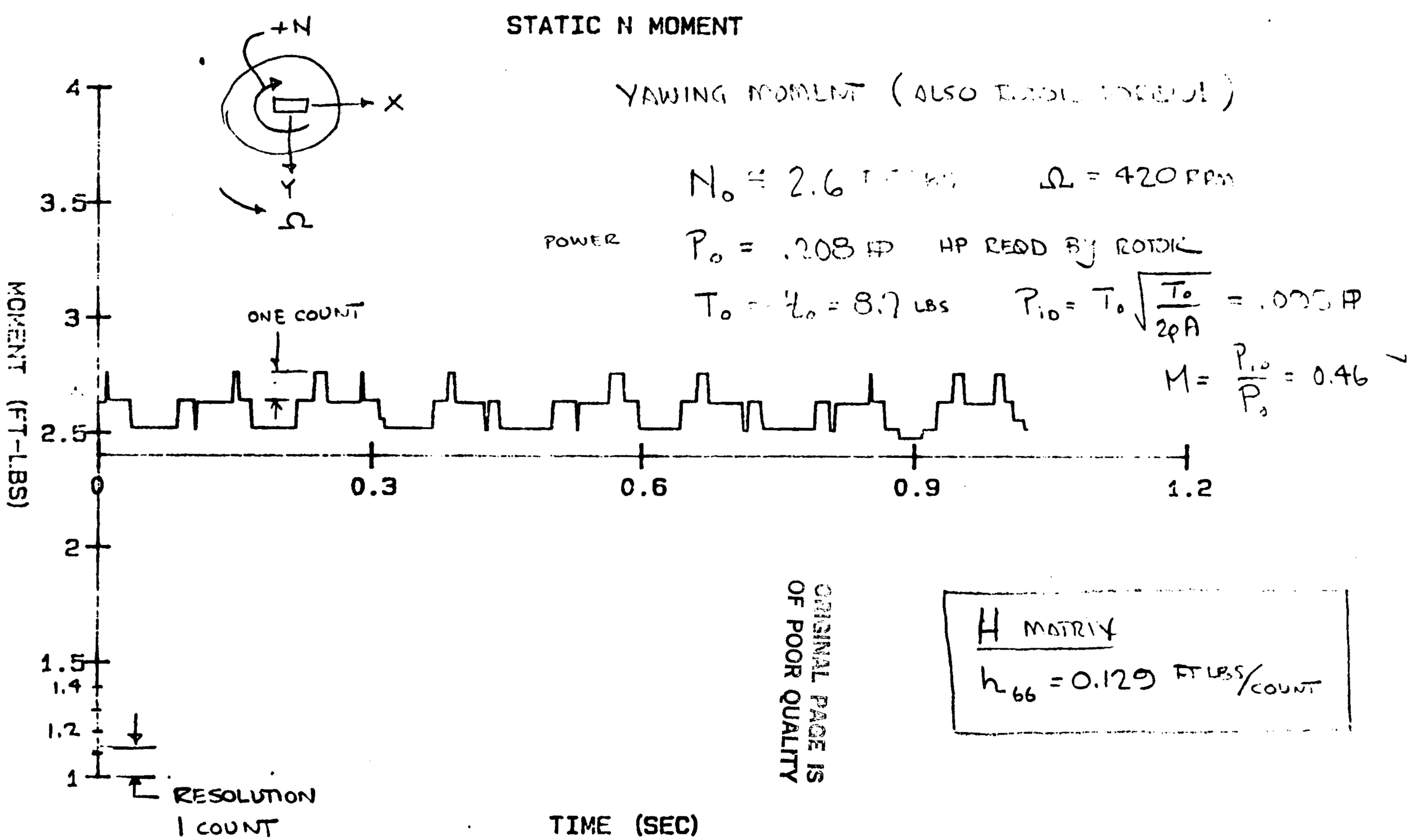
DIAGONALTERM (.0297 FT LBS/COUNT)



(M)

FIGURE 18 - PLOT OF PITCH MOMENT DATA FROM STATIC ROTOR TEST

DIAGONAL TERM (.0763 FT-LBS/COUNT)



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(N)

FIGURE 19 - PLOT OF YAW MOMENT DATA FROM STATIC ROTOR TEST

(DIAGONAL .129 FT LBS/COUNT)

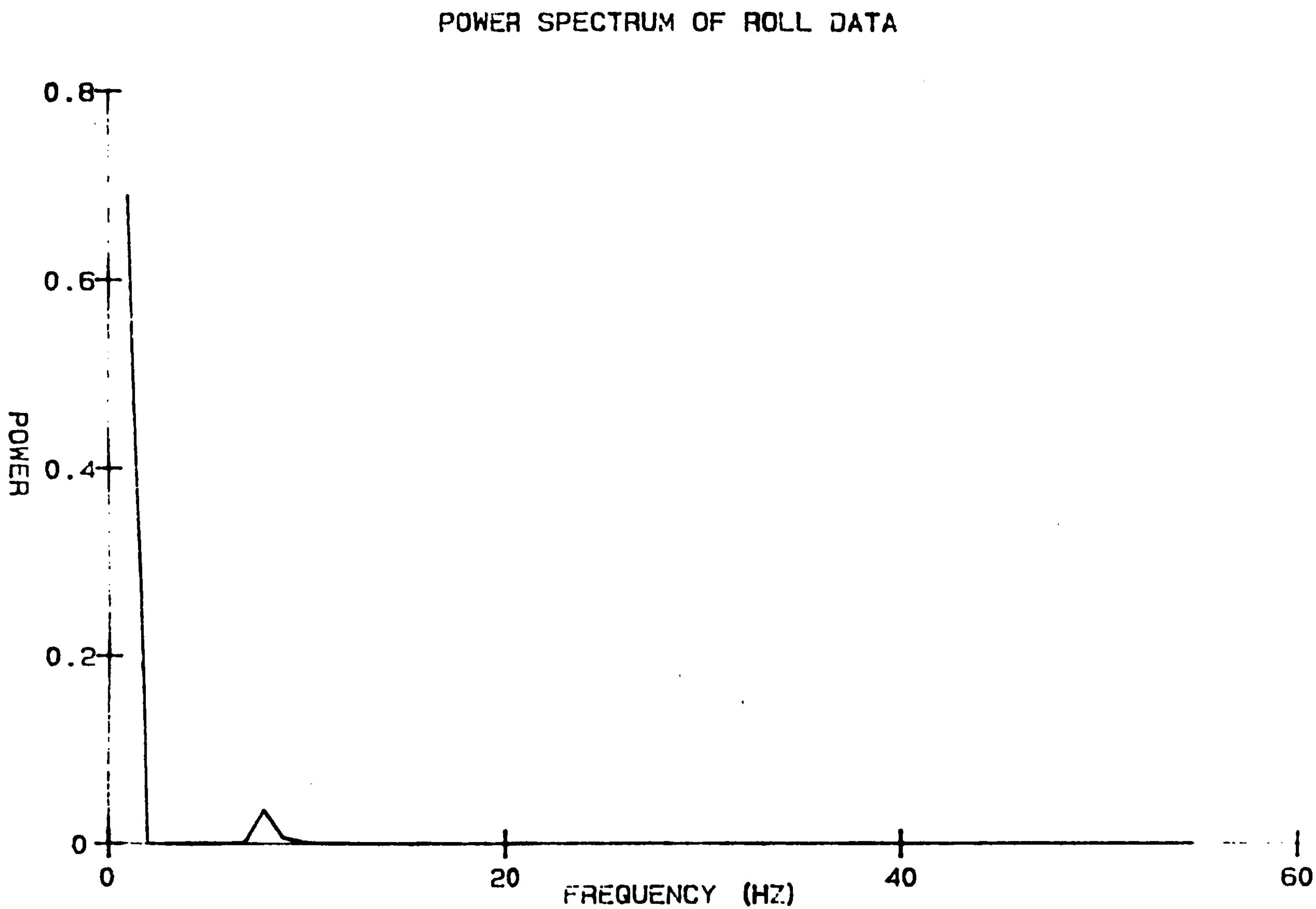
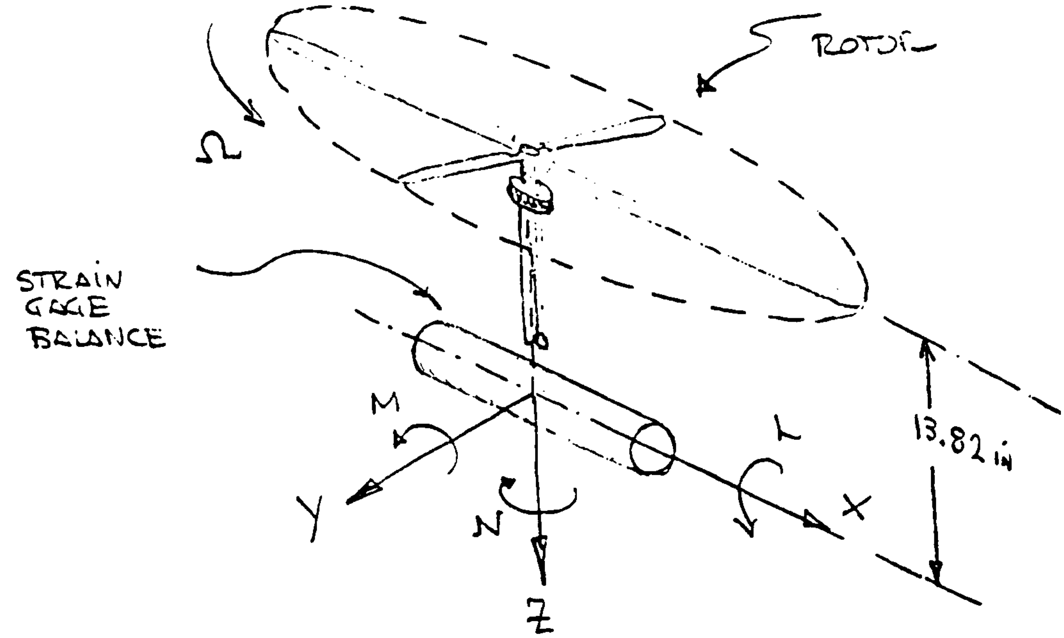
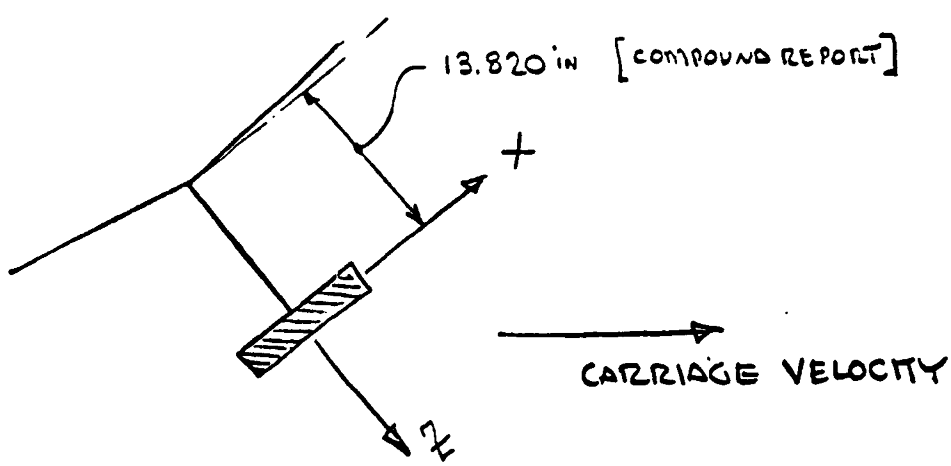


FIGURE 20 - SPECTRAL PLOT OF ROLL MOMENT DATA FROM STATIC ROTOR TEST





BALANCE MEASURES IN SHAFT AXIS SYSTEM

FIGURE 20a BALANCE CONFIGURATION

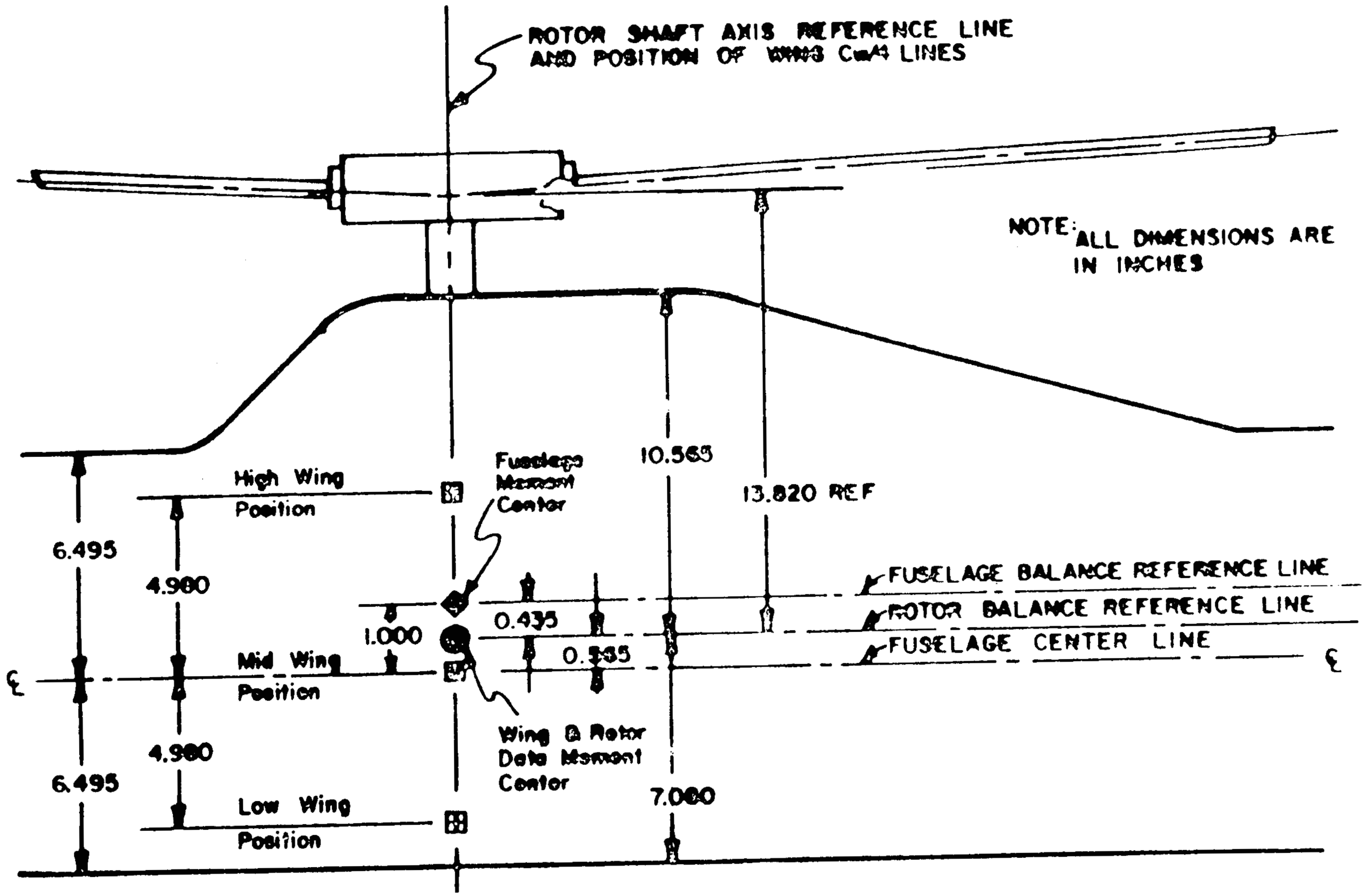


Figure 20b. Model Component Reference Locations.

References:

[1]Technical manual, PDS-700-45, manual #M-4247, AYDIN VECTOR, 31 January 1985.

[2]Technical manual, PAD-400-2, manual #M-4054, AYDIN VECTOR, 31 January 1985.

[3]HSD-16 D.M.A. Digital I/O Card Manual, ICS Computer Products , Inc., 1987.

[4]DOS Technical Reference, First Edition, IBM Corp., February 1985.

[5]Ibid.

[6]Preliminary Calibration of the 1.25 Mk XII A, Internal Balance, document #B-1134, Task Corp., 28 January 1969.

[7]Putnam, W. F., and Traybar, J. J., "An Experimental Investigation of Compound Helicopter Aerodynamics in Level and Descending Forward Flight and in Ground Proximity," USAAMRDL Technical Report 71-19, July 1971.